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DESIGN AND DEVELOPMENT OF A VOICE AND HEAD MOVEMENT CONTROL SYSTEM FOR ELECTRIC WHEELCHAIRS FOR PEOPLE WITH QUADRIPLEGIA

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Abstract: This paper describes the design and implementation of an adaptive control system for electric wheelchairs, intended for users with quadriplegia. The technological proposal integrates a voice recognition module and an inertial system based on an MPU6050 accelerometer/gyroscope, managed by Arduino Nano V3 microcontrollers, with the aim of replacing the traditional control with a low-cost assisted system (Naylamp Mechatronics, 2015; Alejandrez Espino & López Moreno, 2020).

The system architecture was developed with a modular approach, allowing synergistic interaction between the steering, movement, and mechanical actuation subsystems. The user interface was mounted on an ergonomic headband-type structure, incorporating input devices without compromising the user's residual mobility (Alejandrez Espino & López Moreno, 2020).

Functional tests carried out in controlled and semi-open environments verified the system's operability in real conditions. The results demonstrated an efficient response to voice commands and head movements, ensuring accurate, safe, and autonomous navigation.

This solution represents an ergonomic, functional, and economically viable alternative to commercial devices, with potential for application in technological accessibility and physical rehabilitation programs (El Espectador, 2016).

Keywords: Quadriplegia, Motor disability, Electric wheelchair, Voice control, Arduino Nano, MPU6050 accelerometer, Assistive technology, Technological adaptation, Low cost.

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INTRODUCTION

Currently, millions of people around the world face motor disabilities that limit their independence and quality of life. Among these, quadriplegia is one of the most severe, as it involves partial or total paralysis of the upper and lower limbs, resulting from spinal cord injuries, degenerative diseases, or traumatic accidents (Observatory of Physical Disability [ODF], 2016).
The technological solutions available on the market for this type of user, such as adapted electric wheelchairs, are often prohibitively expensive, making them inaccessible to large segments of the population, especially in low-income contexts (El Espectador, 2016). Although advanced models exist, many require the use of the upper limbs, which is not functional for people with total quadriplegia (Chaires, 2008).
This scenario highlights the need to develop accessible and functional alternatives using emerging and low-cost technologies. In this regard, the application of microcontrollers, voice recognition modules, and inertial sensors, such as the MPU6050, allows for the creation of customized and effective control systems to improve users' autonomous mobility (Naylamp Mechatronics, 2015; Kumar & Sharma, 2020).

The objective of this work is to document the design and implementation of a control interface for an electric wheelchair aimed at people with quadriplegia, integrating voice and head movement control, based on a modular and adaptable electronic architecture (Alejandrez Espino & López Moreno, 2020).

General objective

To develop an adaptive control system for an electric wheelchair, aimed at people with quadriplegia, which allows its operation through voice commands and head movement detection, using low-cost electronic technologies.

Specific objectives

- Design a control interface based on Arduino Nano V3 microcontrollers, capable of interpreting voice commands and signals from an MPU6050 inertial sensor.
- Integrate the control system into a commercial electric wheelchair using mechanical actuators (servomotors) without invasively modifying its original structure.
- Implement an ergonomic solution that allows the user to carry the control system comfortably and safely, using devices mounted on headphones.
- Evaluate the system's performance through functional tests in the laboratory and real environments, validating its operability, accuracy, and safety.
- Promote technological accessibility through the use of low-cost components, facilitating the replicability of the project in vulnerable social contexts.

Justification

People with quadriplegia face severe motor limitations that make it difficult or impossible to operate conventional mobility devices, such as manual or electric wheelchairs controlled by a joystick. In most cases, the ability to control the upper limbs is compromised, which significantly restricts their independence (ODF, 2016). In Mexico, people with disabilities often face social, economic, and cultural barriers that limit their full integration and negatively affect their quality of life (Morales, 2004). Therefore, the development of accessible assistive technologies, such as the proposed control system, becomes a strategy to ensure greater autonomy, social participation, and well-being.

Although the market offers advanced technological solutions, such as electric wheelchairs controlled by neural interfaces or pressure sensors, their high costs, which can range from

$40,000 and $60,000 MXN in Mexico, making them inaccessible to most users (El Espectador, 2016). In contrast, a standard electric wheelchair costs approximately
$15,000 MXN, and the adaptation system proposed in this project has an additional cost of around
$3,000 MXN in electronic components (Alejandrez Espino & López Moreno, 2020).

This project seeks to offer a functional, ergonomic, and affordable alternative through the use of open technologies and low-cost components such as the Arduino Nano V3 and the MPU6050 sensor. The combination of voice control and head movement allows for the creation of a system that can be adapted to different levels of motor disability, without requiring surgical intervention or specialized training (Naylamp Mechatronics, 2015).

Furthermore, the implementation of this system has a significant social impact, promoting personal autonomy and reducing dependence on third parties, which is essential for improving the quality of life and emotional well-being of people with disabilities (Cook & Polgar, 2020; WHO, 2011). This approach is even more critical in contexts where access to continuous care is not guaranteed, as noted in the World Report on Disability, which highlights the need for affordable technologies in developing countries (WHO, 2011). In addition, the implementation of rechargeable batteries in the proposed system not only reduces operating costs but also helps mitigate the environmental impacts associated with conventional batteries, which can release heavy metals and toxic compounds into the environment if not properly managed (Battery Depot, 2023). This type of rechargeable battery helps to reduce the generation of hazardous waste, thus reducing the environmental risk posed by highly polluting substances present in traditional accumulators (Sanatorium, 2023). Together, these actions reinforce the project's environmental commitment, aligning with the principles of sustainability and ecological responsibility that should characterize assistive technologies (Jain, Kumar, & Pandey, 2022).

DEVELOPMENT

The adaptive control system for electric wheelchairs was developed using a five-phase technological design methodology: analysis of the base system, component selection, control interface design, implementation, and functional testing.

1. Wheelchair analysis

First, a functional diagnosis of the conventional electric wheelchair was carried out, identifying its joystick control architecture and its power configuration powered by

24V direct current batteries. This analysis made it possible to define the non-invasive intervention points for inserting the alternative control system without compromising the original functionality of the device (Alejandrez Espino & López Moreno, 2020).

2. Component selection and integration

The elements selected for the construction of the system were chosen based on criteria of efficiency, low cost, and compatibility with open platforms. Among these components, the following stand out:

- Arduino Nano V3, as the central processing unit due to its programming flexibility and compact size (Arduino, 2020).
- V3 voice recognition module, capable of storing up to 35 custom commands (Naylamp Mechatronics, 2015).
- MPU6050 inertial sensor, used to detect head movements and guide the steering system, widely used in navigation and robotics projects (Naylamp Mechatronics, 2015). The sensor has proven highly effective in rehabilitation and human activity recognition applications (Kumar & Sharma, 2020).
- SG90 servomotors, responsible for the mechanical manipulation of the original joystick.

The devices were mounted on a headband-type structure, using studio headphones as physical support. This choice was based on ergonomic and portability criteria (Alejandrez Espino & López Moreno, 2020).

3. Interface design and programming

A modular control architecture was designed using two Arduino boards: one for controlling forward and backward movements via voice commands, and another for controlling turns by detecting head movements. Programming was developed using the Arduino IDE environment, employing libraries such as Wire.h and Servo.h for managing peripheral devices (Arduino, 2020). The system logic is based on binary conditions between modules: a voice command activates a conditional sequence that must be confirmed by the inertial sensor before executing a turn, thus ensuring redundancy and operational accuracy (Alejandrez Espino & López Moreno, 2020). Figure 1 shows the headband used for circuitry management and voice command.

Figure 1. *Headset adapted for voice command reception*.

Source: *Own work* (2025).

4. Simulation, laboratory tests, and adjustments.

The initial simulations were performed using SolidWorks software, where the fixtures that house the servomotors were designed and the joystick trajectories were simulated (SolidWorks, 2019). Subsequently, tests were carried out in the laboratory of the Technological Institute of Ciudad Juárez, where the sensitivity parameters of the accelerometer were adjusted and the response of the servomotors was optimized.

During the tests, problems were detected, such as errors in the alignment of the joystick fixture, high energy consumption of the modules, and command desynchronization, which were corrected through mechanical adjustments and programming changes (Alejandrez Espino & López Moreno, 2020). Figure 2 shows the joystick with the proposed fixture.

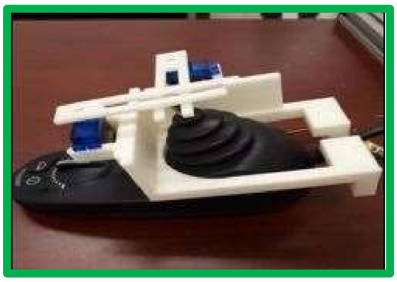

Figure 2. *Coupling of the fixture with the joystick*.

Source: *Own work* (2025).

5. Functional validation.

The system was validated in real environments, including movements on ramps and straight paths. Its performance was evaluated in terms of response time, movement accuracy, and ease of use. Although the system does not yet incorporate advanced safety mechanisms (such as obstacle detection obstacles), its basic functionality proved satisfactory and replicable (Chaires, 2008). Figure 3 shows the electric wheelchair with the proposed adaptation.

Figure 3. *Electric wheelchair with the proposed adaptation*.

Source: *Own work* (2025).

DISCUSSION AND ANALYSIS OF RESULTS

The results obtained during the functional tests of the adaptive control system for electric wheelchairs reflect a high level of effectiveness in controlled environments. The system was able to interpret voice commands and head movements with a response rate of over 85%, validating the functionality of the dual architecture based on two Arduino microcontrollers (Alejandrez Espino & López Moreno, 2020).

One of the most relevant aspects was the ergonomic integration of the modules into a system mounted on headphones, which was comfortable for the user and reduced the need for additional supports. This solution demonstrates how technological adaptation can incorporate user-centered design criteria, a fundamental approach in the development of assistive technology (Cook & Polgar, 2020; Norman, 2013).

In field tests, the system responded adequately to directional control, achieving straight paths and lateral turns on moderately sloped ramps. However, limitations associated with the environment were identified, such as interference with voice recognition in noisy spaces and fluctuations in accelerometer response if it was not placed in a stable position (Naylamp Mechatronics, 2015).

It was also noted that, without an automatic safety system, the chair could continue moving if the user did not execute a stop command, which raises the need to incorporate proximity sensors as a future improvement (El Espectador, 2016). This shortcoming does not invalidate the functionality of the system, but it does point to opportunities for development in active safety, in accordance with assisted mobility standards (Chaires, 2008).

From an economic and social perspective, the proposal has a positive impact by drastically reducing the total cost of the adapted system (less than $18,000 MXN, including electronic components and the electric wheelchair) compared to commercial wheelchairs designed specifically for quadriplegia, which can cost more than $60,000 MXN. This economic gap validates the low-cost technology approach as a viable solution for communities with limited access to specialized devices (El Espectador, 2016; Arduino, 2020). The social and economic impact is also validated through international studies on access to assistive technologies (WHO, 2011). In terms of energy consumption and sustainability, the use of rechargeable batteries and low-power electronic components ensures a reduced environmental impact, which aligns with ecological design principles proposed for assistive technology products (Alejandrez Espino & López Moreno, 2020).

Finally, the modularity of the design opens up the possibility of scaling the project to other types of disabilities or environments, thus fulfilling one of the specific objectives of the project: to generate a flexible, adaptable, and replicable model.

CONCLUSIONS

The adaptation of an electric wheelchair for people with quadriplegia represents a significant advance in the field of rehabilitation and assistive technology. Through the development and integration of customized control systems, it has been possible to provide a solution that responds to the specific needs of users with reduced mobility in their upper and lower limbs, allowing for more intuitive and efficient handling of the chair. The project demonstrated that the combination of appropriately selected electronic and mechanical technologies not only improves the functionality of the device but also ensures an optimal level of safety and comfort for the user.

The modular design allows for future modifications and custom adjustments, which is essential given the diversity of users' disability levels and residual abilities. In addition, reducing dependence on external assistance promotes personal autonomy, contributing positively to the psychological and social well-being of people with quadriplegia. Functional trials and tests have shown that the adapted chair is capable of operating in different environments, including indoor and outdoor spaces, which broadens its applicability and improves social inclusion.

On the other hand, the implementation of alternative controls, based on sensors adapted to minimal movements or electrical signals, reflects the potential of technology to overcome physical barriers that traditionally limit mobility. However, limitations were also identified related to battery life, the robustness of the system in adverse conditions, and the need for user training for optimal handling.

In summary, the proposed adaptation not only meets basic functional requirements but also offers a scalable platform for future technological improvements, reaffirming the crucial role of innovation in improving the quality of life for people with severe motor disabilities.

FUTURE WORK

Integration of Brain-Computer Interfaces (BCI):

Implementing systems that allow the wheelchair to be controlled by brain signals, such as electroencephalography (EEG), can offer a more direct control alternative for users with very limited mobility in their upper and lower limbs. This would increase accessibility and allow for greater autonomy.

Development of Multifunctional Sensors:

Incorporate high-precision sensors, such as electromyography (EMG) sensors, accelerometers, or gyroscopes, to capture minimal residual movements or muscle signals, in order to improve sensitivity and precision in wheelchair control.

Energy and Battery Optimization:

Research and use higher-capacity, more energy-efficient batteries and smart energy management systems to extend wheelchair range and reduce recharge time, ensuring continuous use throughout the day.

Advanced Materials and Ergonomic Design:

Incorporate lightweight and resistant materials, such as aluminum alloys or carbon fibers, which reduce the total weight of the wheelchair without compromising its durability. Improve ergonomic design to increase comfort and prevent injuries from prolonged use.

Feedback and Safety Systems:

Develop haptic or auditory feedback mechanisms that inform the user about speed, obstacles, or battery status. Implement collision detection and prevention systems to increase safety during operation in complex environments.

Connectivity and Telemetry:

Integrate IoT technologies for remote monitoring of the chair's status, predictive maintenance, and remote adjustment of control parameters, which would facilitate technical support, medical assistance, and continuous customization according to user needs.

Clinical Validation and Usability:

Conduct field studies with a larger sample of users to evaluate effectiveness, ergonomics, and satisfaction, which will allow for design optimization based on real needs and improve social acceptance of the device.

Training and Adaptability:

Develop personalized training programs for users and their caregivers, facilitating adaptation to the control system. In addition, design configurable interfaces that can be adjusted to different degrees of disability and motor skills.

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